SINGLE PION PRODUCTION. THEORETICAL DEPENDENCIES AND EXPERIMENTAL LIMITATIONS* **

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The π^0 production in NC interactions of ν_μ constitutes one of the main backgrounds in ν_e appearance measurements of modern long baseline neutrino experiments. This work presents cross-section uncertainty estimates in the context of T2K experiment. The contribution from uncertainty in form factors was found to be at the level of 10%. Additionally, visibility of different π production channels in T2K detectors is examined to verify to what extent T2K itself can measure π production cross-sections.

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1. Introduction

Large uncertainties exist in predicting π meson production cross-sections for low neutrino energy range that is most important for new long baseline experiments (like T2K [1]). The problem is particularly eminent for single π^0 production. Consequently, there are many different theoretical expectations based on different parametrisations of the resonance model that is used to describe π production in this energy range. The T2K experiment will enable to verify them to greater extent. However, those predictions are valuable also in the preliminary stage of the experiment — differences in the π^0 production affect background predictions in Super-Kamiokande and therefore estimations of the expected precision of electron neutrino appearance

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measurements in T2K. The aim of this study is to evaluate cross-section uncertainties and find out what we can measure using T2K detectors to make these uncertainties smaller.

2. Past experiments

Two experiments provided data in the energy region that is of interest for us here. These were ANL (Argonne National Laboratories) and BNL (Brookhaven National Laboratories). Bubble chambers filled with hydrogen or deuterium were used as detectors. More details about these experiments can be found in Ref. [2, 3].

Targets used in the above experiments allow to study primary interactions — the impact of reinteractions in target's nucleus (final state interactions, FSI) is very small. This needs to be taken into account when one wants to extrapolate these results to detectors filled with water or carbon compounds, like tracker detectors in T2K near station's ND280 detector [13]. For such materials FSI play a significant role — to predict cross-sections for specified channels one has to rely also on predictions of FSI model used by the Monte Carlo software.

3. Pion production

The π production channels that are taken into account in this work are (1) $\nu_\mu p \to \mu^- \pi^+ p$, $\nu_\mu n \to \mu^- \pi^+ n$ (CC π^+ production) and (2) $\nu_\mu p \to \nu_\mu \pi^0 p$, $\nu_\mu n \to \nu_\mu \pi^0 n$ (NC π^0 production). In visibility analysis only channels with a proton in the final state will be taken into account, as only such reactions are possible to be measured exclusively.

Dominant channels of π production in T2K energy region are believed to be resonant — they involve resonances, like Δ baryons, as intermediate particles. Technically, resonant production is usually described by Rein–Sehgal model, which takes into account several different resonances. This model is used in Nuance Monte Carlo. However, in low energy region (like the one in T2K) a different model, taking into account only Δ resonances, can be applied with satisfying results. This approach was taken by the authors of NuWro simulation and is called Rarita–Schwinger formalism for the $\Delta(1232)$ excitation (more on simulations in the next section).

Variants of resonance models are usually different in the way the structure functions are parameterized. The vector part of form factors is well known from electron scattering experiments; axial form factors can only be studied in neutrino interactions and hence their form is much less certain. There exist several parameterizations of axial form factors, and NuWro simulation package provides a possibility to choose among some of them. The following three were used in the study:

1. Graczyk Sobczyk "1.2" (GraSob1.2),
2. Graczyk Sobczyk "0.9" (GraSob0.9),
3. Paschos Lalakulich BNL fit (PaschosLal).

They differ in the way the axial form factor $C_A^5(Q^2)$ is defined (Q^2 is four-momentum transfer). In particular, $C_A^5(0) = 1.2$ for parameterization 1 and $C_A^5(0) = 0.89$ for parameterization 2. Value of 1.2 is commonly used in PCAC calculations, 0.9 comes from global fit to data performed by Graczyk and Sobczyk [4, 5] and is also suggested by some new lattice calculation results [7]. For comparison, another parametrisation, devised by Paschos and Lalakulich [6], is also presented here. All of them are results of fits to bubble chamber data.

The aim of this study was to compare neutrino cross-sections predicted by the parameterizations mentioned above, find out what is the cross-section uncertainty in the context of the T2K experiment, and see what is the detectors' potential capability of measuring pion production events.

4. Simulations

The main simulation package used in this analysis was NuWro simulation [9], authored by Wroclaw Neutrino Group. For resonant π production it uses Rarita-Schwinger formalism for the $\Delta(1232)$ excitation. NuWro is a simulation for which many parameters can be specified manually, including axial form-factor parameters, which are of interest to us in this analysis. FSI are gradually being implemented in NuWro, but were not yet applicable for this work.

As a reference, Nuance neutrino generator [8] was used. Nuance is a widely used tool, tested in experiments with water Cherenkov detectors like K2K. Its implementation of final state interactions (FSI) in water is considered trustworthy (this will also be examined further in the text). Nuance will be used in situations where evaluation of impact of FSI is needed and in the visibility analysis.

All simulation samples in this work were created using water as a target — the most suitable material when simulating interactions in Super-Kamiokande or P0D and water FGD (subdetectors of ND280, near station detector of T2K experiment). Only muon neutrino interactions were taken into account as they dominate the T2K beam [13].

5. Cross-section comparison

The idea of this comparison is to see how cross-section uncertainty depends on energy of incoming neutrino. The result is presented in figure 1.

As all the parameterizations described here are results of fits to deuterium or hydrogen data, a cross-check with some water experiment is necessary. K2K experiment offers such a possibility. Its near detector was used to measure a cross-section for inclusive NC π^0 production normalized to cross-section for all CC interactions [10]. This cross-section was found to be equal to $R = \sigma(NC\pi^0)/\sigma(\mathrm{CCtotal}) = 0.064 \pm 0.001(\mathrm{stat}) \pm 0.007(\mathrm{sys})$. The result obtained using Nuance simulation is $R = 0.065$. It agrees well with aforementioned K2K result (and NEUT result quoted in the article [10]).

We can conclude that Nuance is a reliable tool for pion production on water and we will use it as a reference. This conclusion is also supported by the analysis of atmospheric neutrinos in Super-Kamiokande [12]. One can then use its feature to turn off FSI to make it possible to directly compare the results with NuWro (which generates primary interactions only). These two sets of points (with and without FSI) are also presented in Fig. 1.

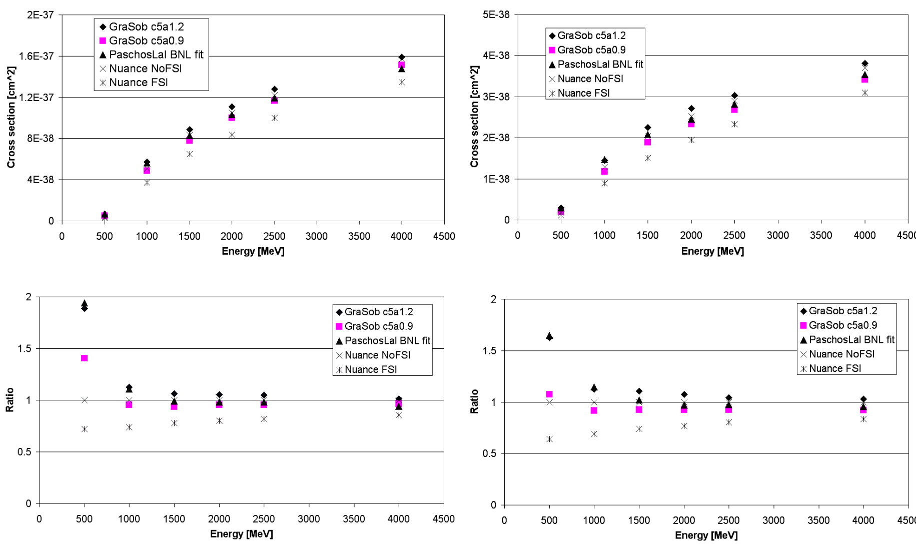

Fig. 1. Cross-sections of ν_μ induced π production on water. Left — CC π^+ production ($\nu p \to \mu^- \pi^+ p$, $\nu n \to \mu^- \pi^+ n$), right — NC π^0 production ($\nu p \to \nu \pi^0 p$, $\nu n \to \nu \pi^0 n$). Top — absolute cross-section values, bottom — cross-sections normalized to Nuance results with no FSI.

All comparisons were done in the channels described earlier. As one can see the most notable differences are present in the NC single π^0 channel. For neutrino energies that we deal with in T2K they range up to 10% in this channel.

We can conclude this part by stating that the cross-section uncertainty is of the order of 10%. However, it is worth to note that we do not take into account uncertainties related to nonresonant background to single π^0 production here — they will probably significantly enlarge the overall cross-section error.

6. Visibility study

We have already seen that large uncertainties are expected in terms of cross-sections. However, some of these cross-sections for water can be measured for T2K beam. One of the goals of ND280, the near detector of T2K, is measuring cross-section for different neutrino interaction processes. In the case of π production, one might want to measure exclusively the $\nu_\mu p \to \mu^- \pi^+ p$ reaction in order to verify the model and then try to extrapolate to NC π^0 production. Below we will try to show what we can learn from measurements in modern high-precision scintillator detectors like P0D and FGD used in ND280. To make our considerations generic, we will not use any specific detector simulation. Instead, some cuts will be imposed on simulated tracks to mimic behavior of the detectors.

Subdetectors in question are divided into layers. Each layer contains two scintillator planes (with scintillator bars in one plane oriented perpendicularly to the bars in the other plane) and a tank with water (a principal target). Such a layer is 6.4 cm thick in the case of P0D and 4.5 cm thick in the case of FGD. A particle has to traverse two perpendicular planes to have its position determined in three dimensions (a single tracking point is recorded).

Since the minimum track length depends on the detector, we have chosen to take into account several possible cuts, each for different length of track. Table I presents the cuts, along with the associated momenta for pions and protons. They were calculated using range-energy curves for water from [11]. The cuts are performed on the z component of momentum (along the beam line), as the layers are oriented perpendicularly to the z axis.

TABLE I

Track length	Proton momentum cut	π^+ momentum cut
6 cm	400 MeV/c	110 MeV/c
10 cm	450 MeV/c	120 MeV/c
14 cm	500 MeV/c	130 MeV/c
18 cm	550 MeV/c	140 MeV/c

Events are classified as belonging to certain type using their visible particles in the final state, *e.g.* for $\nu_\mu p \to \mu^- \pi^+ p$ to be visible, the pion and proton have to have momenta over the visibility thresholds. In Fig. 2 a comparison of different track length cuts in terms of number of visible events is presented. The number of events is normalized to true number of events, *i.e.* the number one gets when no cuts are imposed. It is clear that the

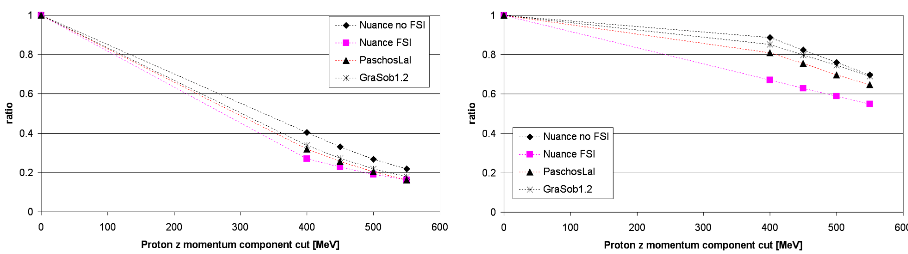

Fig. 2. Number of visible events as a function of momentum cuts (normalized to true number of events). Left — CC π^+ production on protons ($\nu_\mu p \to \mu^- \pi^+ p$), right — NC π^0 production on protons ($\nu_\mu p \to \nu_\mu \pi^0 p$). Only cut values for protons are shown, but related cuts for π^+ (as specified in Table I) are also imposed in the same time for π^+ production.

detectors can reconstruct only a fraction of π's. Larger decrease of number of events is observed in the CC channel (more than 60%), due to cut on protons and π^+s in the same time (for the NC channel the cut is performed only on protons as π^0s are considered always visible). Charged pions tend to have lower momenta than protons — this is due to Pauli blocking, which forces most of the nucleons to have larger momentum. That is why most of events with charged pions get discarded. It is unfortunate, since this channel is one of the easiest to measure.

It can also be seen that FSI change the detection capability, so their good implementation in simulations is essential for reliable visibility predictions. It also follows that model verification with $\nu_\mu p \to \mu^- \pi^+ p$ measurements is difficult in low Q^2 region. The measurement-based approach to π^0 background determination will therefore involve also model uncertainties.

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